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Utilization of Carbonized Wastes as Ethylene Absorbers for Shelf-life Extension of Major Tropical Fruits in Southern Philippines

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ABSTRACT

Background: Climacteric fruits are a significant concern in the Philippines due to their perishable nature and sensitivity to environmental factors. Variables such as temperature fluctuations, changing rainfall patterns and the increased frequency of extreme weather events negatively affect fruit production, quality and shelf life. Implementing climate-resilient agricultural practices can help mitigate the impacts of climate change on fruit production. Techniques such as ethylene absorption or inhibition can potentially delay ripening and reduce spoilage of climacteric fruits.

Methods: This study was conducted to examine the effects of carbonized wastes on extending shelf life and improving the fruit quality of selected climacteric fruits (mango, papaya and banana). A completely randomized design (CRD) was used with five treatments: control, carbonized banana peels (CBP), carbonized corn husks (CCH), carbonized peanut shells (CPS) and potassium permanganate (standard check), each replicated four times. The carbonized agricultural wastes were applied during the storage of the selected fruits and postharvest quality parameters were assessed.

Result: Among the treatments evaluated, carbonized banana peels (CBP) and carbonized peanut shells (CPS) delayed the ripening of climacteric fruits ('Carabao' mango, 'Red Solo' papaya and 'Cavendish' banana) stored under ambient room conditions. These fruits reached the limit of marketability (VQR 3) within 6-18 days of storage. The least cumulative weight loss and delayed color change were also recorded in the same treatments, which significantly improved the postharvest quality of the fruits. Based on these findings, carbonized wastes can be recommended as alternative ethylene absorbers for producers, distributors and retailers to extend shelf life, enhance market value and maintain postharvest quality of climacteric fruits.

Key words: Carbonized agricultural waste, Climacteric fruits, Ethylene absorber, Postharvest quality.

INTRODUCTION

Over the past ten years, global production of tropical fruits had increased significantly, mostly in response to rising demand in main producing regions (FAO, 2021). The fruit and nut growing industry is predicted to increase from $1.19 trillion in 2023 to $1.32 trillion in 2024, with a compound annual growth rate of 10.2% (The Business Research Company, 2024). Tropical fruits which were mostly grown in Asia and Latin America were expected to reach roughly 11 million tons by 2023 as the global commerce for fruits expands. Trade in tropical fruits boosts also the food security of many nations by giving smallholder farmers a significant income through exports, (FAO, 2021).

In the Philippines, the fruit crop operations are an important part of the agricultural economy and contributes a substantial amount to both export earnings and local consumption in the country. The Philippines is also a significant exporter of important fruit crops such as pineapples, mangoes and bananas worldwide (Briones, 2009 and DOST-PCAARRD, 2020). In the first quarter of 2024, bananas alone accounted for 0.234 million metric tons, or almost 50.30% of the entire fruit crop production (PSA, 2024).

There were top five major fruit crops in the Philippines, namely banana, pineapple, papaya, mango and calamansi. In SOCCSKSARGEN region located at the Southern part of the Philippines, bananas are considered as the top fruit crop produced, accounting for 50.30% of total production, followed by pineapples with 44.9%, other important fruits produced are papaya, mango and calamansi (PSA, 2024). These major fruit crops in the Region XII in the island of Mindanao contributes to the economic increases in agricultural sector in the Philippines.

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Postharvest losses in the Philippines are significant for major fruits crops in the Philippines. Causes of postharvest losses include inadequate storage and transportation facilities, poor handling practices and lack of postharvest facilities especially on small scale farms. It is also considered a worldwide problem which made a serious impact on economy, income of farms and food security developing nations like the Philippines. Oliveira *et al*. (2024) highlighted that ethylene gas is released during respiration promotes senescence. In the end, it changes the texture, color and taste of the fruit. According to Asrey *et al*. (2023) controlling the ethylene levels can enhance the postharvest quality of fruit by delaying senescence and lowering decay rates.

Agricultural waste was often underexplored, underutilized and contributing to environmental pollution. Recent research has demonstrated the potential of agricultural waste as an ethylene adsorber, which delays fruit ripening and preserves quality in appropriate packaging (Charoensuk *et al*., 2024; Oliveira *et al*., 2024; Suraj *et al*., 2023). In addition, agricultural waste is sustainable solution for postharvest losses by extracting useful phytochemicals from fruit and vegetable processing to block the increasing amount of ethylene gas (Oliveira *et al*., 2024; Kumar *et al*., 2020).

Recent studies published in ARCC Journals underscore the importance of postharvest interventions and active scavenger systems in extending the shelf life and quality of horticultural produce findings that support the rationale for using carbonized agricultural wastes as ethylene absorbers. *Shelf Life Extension of Minimally Processed Jackfruit* documented the use of $KMnO_4$ as an ethylene scavenger sachet to influence ripening and quality changes in jackfruit portions, highlighting how ethylene oxidation can modify postharvest dynamics (Gana and Mini, 2023). Similarly, research on Innovative Post harvest Treatments to Enhance the Shelf life and Quality of Papaya demonstrated that targeted postharvest treatments, including salicylic acid and chitosan applications, can significantly delay ripening and preserve quality attributes of climacteric fruits by modulating physiological and biochemical responses associated with ethylene driven senescence (Kasilingam *et al*., 2025). Additionally, the broader role of carbonaceous materials such as biochar in agricultural systems is reviewed in Biochar-a Promising Soil Additive, which discusses the high surface area and stable porous structure of biochars derived from biomass a property directly relevant to gas adsorption applications including ethylene capture (Coumaravel *et al*., 2025). Together, these ARCC studies provide context for the development and application of carbonized waste derived absorbers in delaying ripening and extending the marketability of tropical fruits.

The postharvest quality of fruit crops is a key concern in agriculture and food supply because of the perishable nature and rapid deterioration of harvested fruit crops. A novel postharvest technique called ethylene adsorbers improves postharvest quality of the fruit by controlling their ripening and preserving their freshness during storage and transportation (Marc and Muresan, 2024; Anjali *et al*., 2024). Ethylene scavengers like potassium permanganate, activated carbon and biochar made from carbonization material help to decrease the levels of ethylene that can be applied and utilized under storage circumstances include (Sugianti *et al*., 2022; Charoensuk *et al*., 2024; Oliveira *et al*., 2024; Suraj *et al*., 2023).

Many research works have investigated the efficacy of commercially available ethylene adsorbers in regulating the ripening process and extending the shelf life of various climacteric fruits, but they're still few research on the use of carbonized materials from agricultural waste as potential ethylene absorbers. Exploring organic ethylene absorbers can develop more effective, sustainable and eco-friendly solutions for managing ethylene levels in climacteric fruits and ultimately reducing post-harvest losses. Thus, this study was conducted, that aims to develop an effective organic ethylene absorber which can be used by farmers and producers of climacteric fruits particularly in banana, papaya and mango in Southern Philippines for improved fruit quality and contribute to a more sustainable food system.

MATERIALS AND METHODS

Collection of agricultural wastes

Agricultural wastes to be carbonized were collected from the public market of Tacurong City, Sultan Kudarat, Philippines. The collected materials included fresh banana peels (Cardava variety), peanut shells (light to reddish brown) and corn husks (green to light yellow). After collection, these agricultural wastes were immediately dried under full sunlight for 6-8 hours daily (9:00 a.m. to 3:00 p.m.) for five consecutive days.

Carbonization process of dried agricultural wastes

After drying, the agricultural wastes were cut into small pieces and placed inside metal carbonizing containers with small perforation holes to allow airflow for a successful carbonization process. The containers were surrounded by burning charcoal and the heat was sustained for eight (8) hours at a temperature ranging from 34-36°C. Uniform carbonization was ensured by regularly adding ignited charcoal and mixing the dried wastes to prevent overburning and ash formation. After carbonization, the materials were cooled at room temperature for eight (8) hours, then ground into fine powder using a blender. The powdered carbonized materials were packed in breathable sachets (10 g capacity) and stored in sealed containers to be used as ethylene absorbers. For the commercial check, 5 g of potassium permanganate were packed in a breathable sachet.

Fruit sample collection

Fruit samples used in the experiment were collected from various orchards located within the provinces of North and South Cotabato, Philippines. The criteria for fruit selection

were as follows: 'Red Solo' papaya-harvested from a 1-year-old papaya tree at maturity index 1 (10% yellow surface coloration) from Canlas Fruit Orchard, Brgy. Cebuano, Tupi, South Cotabato, Philippines (6.3819°N, 124.9617°E; elevation: 244.33 masl).'Cavendish' banana -harvested from a 1.5- year-old banana plant at commercial green maturity index (115 days after flowering) from AG Farm, Brgy. Minapan, Tulunan, North Cotabato, Philippines (6.7942°N, 124.9130°E; elevation:38.8 masl). 'Carabao' mango-harvested from 10-year-old trees at commercial green maturity index (115 days after flowering) from Gabriel Fruit Production and Processing, Brgy. Sibsib, Tulunan, North Cotabato, Philippines (6.8232°N, 124.8944°E; elevation: 25.7 masl).

All harvested fruits were carefully selected for uniformity in size, shape and external color and were free from bruises, skin diseases and physical injuries. The samples were treated with potassium alum solution and placed in boxes (40 cm × 30 cm × 23 cm). Each box contained a uniform weight of 475 g ('Red Solo' papaya), 682.5 g ('Cavendish' banana) and 312 g ('Carabao' mango), measured using a digital weighing scale.

Experimental Set-up

The study was laid out in a Completely Randomized Design (CRD) with five (5) treatments replicated four (4) times. A total of ten (10) fruits per treatment were used, amounting to 200 sample fruits per commodity. Each set of ten fruits was placed in a 40 cm × 30 cm × 23 cm box. For each box, one sachet (6 × 8 cm, white non-woven breathable fabric) containing the respective treatment was placed. The ethylene absorber sachets were fabricated from white non-woven, polypropylene-based breathable fabric (6 × 8 cm) to permit unrestricted gas diffusion while preventing direct contact between the carbonized material and the fruit surface. Each sachet was filled with 10 g of finely powdered carbonized agricultural waste and sealed by heat bonding to ensure uniform exposure during storage. All sample fruits were stored under ambient room conditions (28±1°C and 85-90% relative humidity) at Marcelino Residence, Postharvest Laboratory, Brgy. San Pablo, Tacurong City, Philippines.

Data collection and statistical analysis

Postharvest quality parameters of the fruits were evaluated within 7-16 days of storage ('Carabao' mango-7 days; 'Red Solo' papaya-12 days; 'Cavendish' banana-16 days). The parameters measured included Visual Quality Rating (VQR), firmness, color change and relative fresh weight. VQR was rated using a 9-point scale: 9.00-7.01: Excellent; field fresh; no defects, 7.00-5.01: Good; minor defects, 5.00-3.01: Fair; moderate defects; limit of marketability, 3.00-1.01: Poor; serious defects; threshold for consumption, <1.00: Unfit for consumption. Firmness and color change were rated using the following scale: 0.00: Firm, no color change, 0.01-1.99: 1-25% softening and color change, 2.00-2.99: 26-50% softening and color change, 3.00: >51% softening and color change. Cumulative weight loss was determined by recording the initial fruit weight prior to treatment application and monitoring changes over time (Kader and Cantwell, 2010). Data were analyzed using the Statistical Tool for Agricultural Research (STAR) software version 2.0. Significance was determined at the 5% level and treatment differences were analyzed using the Friedman test.

RESULTS AND DISCUSSION

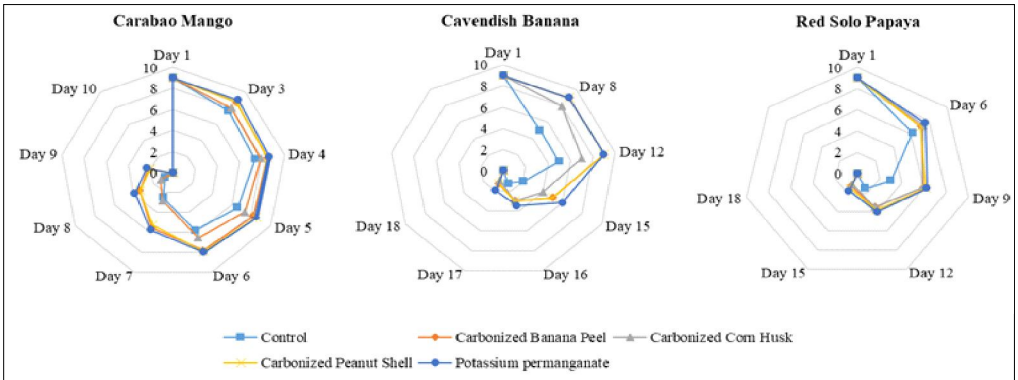
Storage duration varied among fruit commodities according to their physiological maturity and ripening behavior. 'Carabao' mango was evaluated for 7 days, 'Red Solo' papaya for 12 days and 'Cavendish' banana for up to 18 days under ambient room conditions (28±1°C; 85-90% relative humidity). In 'Cavendish' banana, fruits treated with carbonized ethylene absorbers and potassium permanganate reached the limit of marketability (VQR = 3) between 16 and 18 days of storage, depending on the treatment applied, whereas untreated fruits reached this threshold considerably earlier. These storage durations were therefore used to evaluate shelf-life extension and treatment effectiveness across commodities.

Visual quality

Based on Fig 1, the hedonic rating scale for Visual Quality Rating (VQR) of 'Carabao' mango (a), 'Cavendish' banana (b), 'Solo' papaya (c), revealed that the application of carbonized materials as ethylene absorbers effectively delayed fruit deterioration compared to the control. Among the carbonized treatments-banana peel, corn husk and peanut shell-all showed longer storage life, as the fruits only reached VQR 3 at 16 days (Fig 2) for cavendish banana, 12 days for papaya (Fig 3) and 7 days for carabao mango (Fig 4). These results were comparable to the performance of the standard check, potassium permanganate, which is widely recognized for its ethylene-absorbing capacity. In contrast, the control treatment, which did not receive any ethylene absorber, attained VQR 3 at a much earlier time, indicating faster deterioration and reduced shelf life. This highlights the critical role of ethylene absorbents in slowing down ripening and senescence processes by reducing ethylene accumulation in the storage environment.

Peel color change

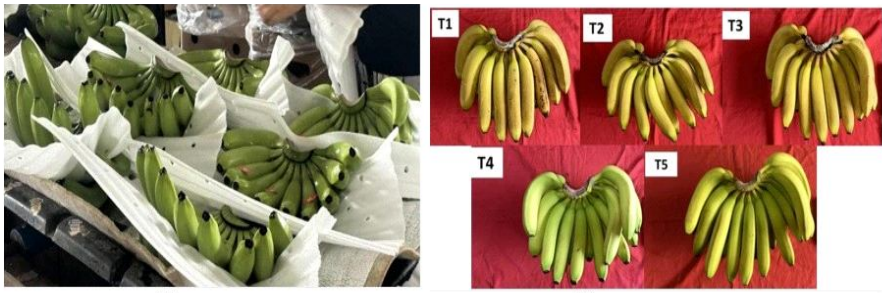
As shown in Fig 5, the hedonic rating scale for peel color change revealed that the application of ethylene absorbers effectively delayed the ripening process of 'Red Solo' Papaya, 'Cavendish' banana and 'Carabao' mango. Among the evaluated treatments, carbonized peanut shell and potassium permanganate exhibited the great effect in prolonging the visual quality of papaya and banana. These fruits reached above 50% peel color change, indicating the stage of near ripeness, only after 15-18 days of storage. This suggests that both treatments were successful in suppressing ethylene action and slowing down the ripening process, thereby extending shelf life. For mango, all carbonized treatments including carbonized banana peel,



Fruits were evaluated using a 9-point hedonic scale, where VQR = 3 represents the limit of marketability. Carbonized banana peel and carbonized peanut shell treatments consistently delayed visual deterioration compared with the control.

Rating scale:
9.00-7.01 (Excellent; field fresh; no defects).
7.00-5.01 (Good; minor defects).
5.00-3.01 (Fair; moderate defects, limit marketability).
3.00-1.01 (Poor; serious defects; threshold for consumption).
>1.00 (Unfit for consumption).

Fig 1: Changes in visual quality rating (VQR) of (a) 'Carabao' mango, (b) 'Cavendish' banana, and (c) 'Red Solo' papaya during storage under ambient room conditions (28±1°C, 85-90% RH) treated with different ethylene absorbers.



(A) (B)

T_1-Control, T_2-Carbonized banana peel, T_3-Carbonized corn husk, T_4-Carbonized peanut shell and T_5-Potassium permanganate. Carbonized treatments visibly delayed peel yellowing and senescence.

Fig 2: Representative appearance of 'Cavendish' banana fruits at (A) Field fresh (Day 1) and (B) after 15 days of storage under ambient room conditions (28±1°C, 85-90% RH) treated with different ethylene absorbers.



(A) (B)

T_1-Control, T_2-Carbonized banana peel, T_3-Carbonized corn husk, T_4-Carbonized peanut shell and T_5-Potassium permanganate. Fruits treated with carbonized banana peel and peanut shell retained better visual quality compared with untreated.

Fig 3: Representative appearance of 'Red Solo' papaya fruits at (A) Field fresh (Day 1) and (B) after 12 days of storage under ambient room conditions (28±1°C, 85-90% RH) treated with different ethylene absorbers.

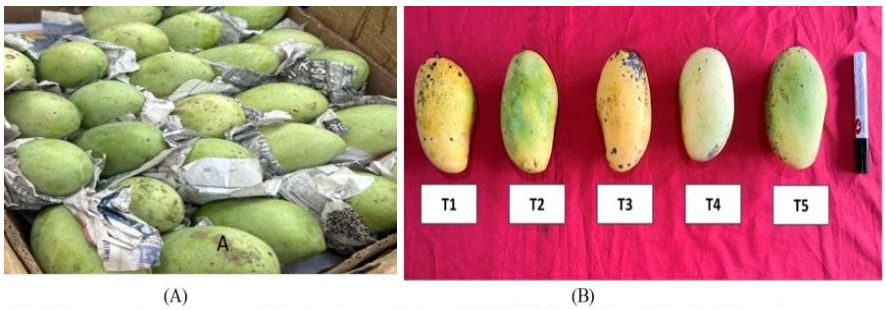
corn husk and peanut shell showed a significant delay in peel color change, which became evident at 8 days of storage. Their effects were comparable to the standard check (potassium permanganate), confirming the potential of carbonized by-products as viable alternatives to commercial ethylene absorbers. In contrast, fruits stored without any ethylene absorber (control) exhibited earlier color changes. For papaya and banana, noticeable changes in peel color were observed as early as 8-9 days of storage, which is considerably earlier compared to treated samples. This rapid ripening in untreated fruits highlights the important role of ethylene absorbers in managing postharvest quality.

Firmness index

In Fig 6, the hedonic rating scale for firmness of 'Carabao' mango (a), 'Cavendish' banana (b) and 'Solo' papaya (c), illustrates the effectiveness of carbonized treatments in maintaining fruit quality during storage. The results indicate that all carbonized treatments specifically carbonized banana peel, carbonized corn husk and carbonized peanut shell were comparable to the standard check treatments in delaying the decline in firmness. For Cavendish banana, fruits treated with carbonized materials exhibited a slower reduction in firmness, reaching the firmness index of 3 at above 50% only after 18 days of storage. Similarly, Red Solo papaya showed delayed softening under carbonized treatments, attaining the same index at 15 days of storage. In the case of Carabao mango, firmness was retained until 9 days of storage, which is longer compared to untreated or less effective treatments.

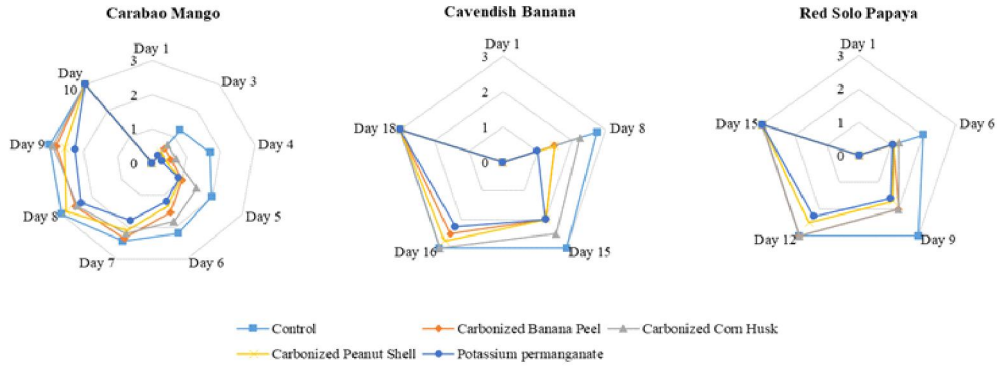
Cumulative weight loss

As shown in Table 1, the cumulative weight loss percentage across the three climacteric fruits demonstrated the



T_1-Control, T_2-Carbonized banana peel, T_3-Carbonized corn husk, T_4-Carbonized peanut shell and T_5-Potassium permanganate. Carbonized treatments delayed peel color change and surface deterioration compared to control.

Fig 4: Representative appearance of 'Carabao' mango fruits at (A) Field fresh (Day 1) and (B) after 7 days of storage under ambient room conditions (28±1°C, 85-90% RH) treated with different ethylene absorbers.



Color change was rated using a hedonic scale based on the percentage of surface discoloration. Carbonized peanut shell and potassium permanganate treatments effectively delayed color development associated with ripening.

Rating scale:

0.00 (No color changes).

0.01-1.99 (1%-25% color changes).

2.00-2.99 (26%-50% color changes).

3.00 (>51% color changes).

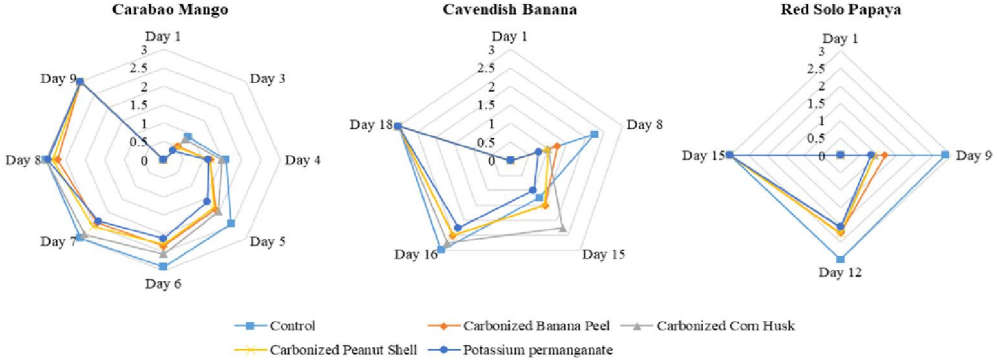
Fig 5: Peel color change progression of (a) 'Carabao' mango, (b) 'Cavendish' banana and (c) 'Red Solo' papaya stored under ambient room conditions (28±1°C, 85-90% RH) with different ethylene absorbers.

effectiveness of carbonized materials as ethylene absorbers in reducing postharvest deterioration. Among the treatments applied, the lowest weight loss was consistently observed in fruits treated with carbonized by-products, highlighting their potential in minimizing water loss and maintaining fruit freshness during storage.

For Carabao mango, samples treated with carbonized peanut shell recorded the least weight loss (4.58%), indicating its superior ability to delay physiological processes that lead to moisture loss at 6 days of storage. In Red Solo papaya, treatments with carbonized banana peel (4.78%), carbonized corn husk (4.99%) and carbonized peanut shell (5.67%) also exhibited lower cumulative weight loss compared to other treatments at 12 days of storage. Similarly, in Cavendish banana, the least weight loss was observed in fruits treated with carbonized banana peel (4.90%) and carbonized peanut shell (4.66%) at 15 days of storage. In contrast, untreated fruits typically experience faster ripening and metabolic activity, resulting in higher weight loss and reduced storage life.

These findings suggest that carbonized materials effectively reduce the rate of fruit softening, enhance the visual quality, delay change in color and reduce cumulative weight loss likely due to their ability to absorb ethylene and suppress its accumulation in storage environments. Ethylene plays a central role in ripening by enhancing cell wall degradation and softening; thus, its absorption prolongs the shelf life of climacteric fruits such as papaya, banana and mango. The comparable performance of carbonized by-products to the standard check treatments underscores their potential as low-cost, sustainable alternatives for postharvest handling.

The study showed that carbonized agricultural wastes such as banana peels, peanut shells and corn husks can serve as viable alternatives to potassium permanganate ($KMnO_4$) for maintaining the postharvest quality of



Firmness was assessed using a hedonic scale based on the degree of softening. Carbonized banana peel and peanut shell treatments maintained higher firmness levels, indicating delayed ripening.

Rating scale:
0.00 (Firm).
0.01-1.99 (1%-25% softening).
2.00-2.99 (26%-50% softening).
3.00 (>51% softening).

Fig 6: Firmness changes of (a) 'Carabao' mango, (b) 'Cavendish' banana, and (c) 'Red Solo' papaya during storage under ambient room conditions (28± 1°C, 85-90% RH) treated with various ethylene absorbers.

Table 1: Cumulative weight loss (%) of 'Carabao' mango (6 days), 'Red Solo' papaya (12 days) and 'Cavendish' banana (15 days) stored under ambient room conditions (28±1°C, 85-90% RH) and treated with different ethylene absorbers.

Treatments (Ethylene absorbers)	6th Day of storage** ('Carabao' mango)	12th day of storage* ('Red solo' papaya)	15th day of storage** ('Cavendish' banana)
Control (Without application)	7.23^{b}	8.89^{b}	9.19^{c}
Carbonized banana peel	6.55^{b}	4.78^{a}	4.90^{a}
Carbonized corn husk	7.14^{b}	4.99^{a}	5.53^{ab}
Carbonized peanut shell	4.58^{a}	5.67^{a}	4.66^{a}
Potassium permanganate	2.73^{ab}	5.69^{a}	7.32^{bc}

(Standard check).
**-Highly significant.
Means with different superscript letters within a column are significantly different at p<0.05 (Friedman test).

climacteric fruits. Among the evaluated carbonized treatments, carbonized peanut shells and banana peels exhibited results most comparable to $KMnO_4$ when evaluated in terms of relative fresh weight (least cumulative weight loss), visual quality rating, firmness and peel color changes in 'Carabao' mango, 'Cavendish' banana and 'Red Solo' papaya.

One of the important indicators of postharvest deterioration is relative fresh weight (RFW), which reflects the extent of moisture loss due to transpiration. Untreated fruits consistently recorded the lowest relative fresh weight (high percentage of cumulative weight loss), highlighting the function of water loss as a primary factor in postharvest decline. In contrast, mangoes treated with carbonized peanut shells maintained significantly higher relative fresh weigh values than untreated fruits, with performance comparable to those treated with $KMnO_4$. In contrast, carbonized corn husks showed relatively lower efficacy, likely due to differences in biomass composition and pore development. Corn husk derived biochar typically exhibit lower surface area and less uniform pore size distribution, which may limit ethylene adsorption efficiency compared with peel- and shell-derived biochar (Wang *et al*., 2023; Saberi *et al*., 2024). These findings highlight that adsorption performance is strongly influenced by the intrinsic properties of the original biomass rather than carbonization alone. Banana peels are naturally rich in cellulose, hemicellulose and pectin, which, after carbonization, form a highly porous carbon structure. This porous matrix enhances the physical adsorption of small gaseous molecules such as ethylene. Peanut shells contain a high proportion of lignin, resulting in a more aromatic and structurally stable carbon framework after carbonization. The improved pore connectivity of this material supports more consistent ethylene adsorption across all climacteric fruits evaluated (Leng *et al*., 2021; Charoensuk *et al*., 2024; Oliveira *et al*., 2024). Charoensuk *et al*. (2024) further reported that rice husk biochar exhibited an ethylene adsorption rate of 31.13% after 144 hours, underscoring the potential of biochar in delaying ripening. Comparable results were noted by Bailén *et al*. (2006), who found that tomatoes stored with granular activated carbon exhibited reduced ethylene accumulation and lower weight loss. Similarly, Yahia (2012) emphasized that even slight reductions in ethylene exposure could significantly minimize water loss, particularly in high-respiring fruits.

In terms of visual quality rating (VQR), all climacteric fruits showed a natural decline over time, consistent with expected ripening behavior. However, fruits treated with $KMnO_4$, carbonized peanut shells and banana peels retained higher VQR values compared to untreated controls. While untreated fruits exhibited accelerated senescence and visible signs of deterioration, treated fruits maintained VQR values within the ranges of 9.00-7.01 ("excellent" to "field fresh") and 7.00-5.00 ("good" to "minor defects") for longer storage periods. These results support earlier findings that carbonized agricultural wastes can effectively delay ripening while minimizing visual defects that strongly influence consumer preference and marketability (Wills *et al*., 2007). Likewise, Tran *et al*. (2024) highlighted the role of activated carbon-based ethylene scavengers in preserving fruit appearance and extending shelf life.

Peel color change is another prominent indicator of fruit ripening, driven by ethylene-induced chlorophyll degradation and pigment conversion. Fruits treated with carbonized peanut shells and banana peels demonstrated significantly delayed color transitions, performing similarly to $KMnO_4$. These results are consistent with the findings of Saltveit (1999), who reported that reducing ethylene exposure delays chlorophyll breakdown and preserves the visual appeal of fruits. Thus, the ability of carbonized treatments to adsorb ethylene likely contributed to the slower progression of color changes and delayed visible ripening symptoms.

Firmness as a vital textural attribute reflecting ripening and structural integrity, also declined more gradually in fruits treated with $KMnO_4$, carbonized banana peels and peanut shells compared to untreated controls. In Cavendish bananas, these treatments maintained significantly higher firmness values than both untreated fruits. The delayed softening observed in treated fruits supports the role of ethylene adsorption in limiting cell wall degradation by suppressing the activity of polygalacturonase and related enzymes responsible for tissue softening (Lurie and Pedreschi, 2014).

The findings confirm that carbonized agricultural wastes, particularly peanut shells and banana peels, exhibit comparable effectiveness to $KMnO_4$ in delaying fruit ripening and preserving quality attributes. Unlike $KMnO_4$, which raises food safety concerns (Álvarez-Hernández *et al*., 2019; Payyadakkath *et al*., 2022), carbonized plant-based materials are eco-friendly, low-cost and safe alternatives. Their demonstrated capacity to extend shelf life, maintain consumer-acceptable quality and reduce postharvest losses that highlights their strong potential for practical application in sustainable postharvest management.

CONCLUSION

In conclusion, carbonized agricultural wastes, particularly carbonized peanut shells and banana peels, demonstrated strong potential as sustainable alternatives to potassium permanganate for ethylene scavenging and shelf-life extension of climacteric fruits. Their effectiveness in delaying ripening, maintaining firmness, reducing weight loss and preserving visual quality highlights their important applicability in practical postharvest management. The utilization of these low-cost, eco-friendly materials offers a viable strategy for reducing postharvest losses, enhancing farmer income and promoting circular agriculture in the tropical fruit industry of Southern Philippines.

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Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Informed consent

Not applicable. No humans or animals were used in the study.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

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